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Abstract: We report the first major study of cryptotephra (non-visible volcanic ash layers) on Late Palaeolithic archaeological sites in northern Europe. Examination of thirty-four sites dating from the Last Termination reveals seven with identifiable cryptotephra layers. Preservation is observed in minerogenic and organic deposits, although tephra is more common in organic sediments. Cryptotephra layers normally occur stratigraphically above or below the archaeology. Nearby off-site palaeoclimate archives (peat bogs and lakes <0.3 km distant) were better locations for detecting tephra however only indirectly can the archaeology be correlated with the cryptotephra. Patterns affecting the presence/absence of cryptotephra include geographic position of sites relative to the emitting volcanic centre; the influence of past atmospherics on the quantity, direction and patterns of cryptotephra transport; the nature and timing of local site sedimentation; sampling considerations and subsequent taphonomic processes. Overall, while tephrostratigraphy has the potential to improve significantly the chronology of such sites many limiting factors currently impacts the successful application.

***Highlights (for review)**

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- Cryptotephra study of 34 north European Late Palaeolithic archaeological sites.
- Seven sites have identifiable cryptotephra layers.
- Best preservation occurs in low-energy off-site palaeoclimate archives.
- Geographic position to emitting centre and past atmospherics are influential.
- In situ sediment record, preservation and taphonomy impact on outcomes.

Examination of Late Palaeolithic archaeological sites in Northern Europe for the preservation of cryptotephra layers

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Abstract: We report the first major study of cryptotephra (non-visible volcanic ash layers) on Late Palaeolithic archaeological sites in northern Europe. Examination of thirty-four sites dating from the Last Termination reveals seven with identifiable cryptotephra layers. Preservation is observed in minerogenic and organic deposits, although tephra is more common in organic sediments. Cryptotephra layers normally occur stratigraphically above or below the archaeology. Nearby off-site palaeoclimate archives (peat bogs and lakes <0.3 km distant) were better locations for detecting tephra however only indirectly can the archaeology be correlated with the cryptotephra. Patterns affecting the presence/absence of cryptotephra include geographic position of sites relative to the emitting volcanic centre; the influence of past atmospherics on the quantity, direction and patterns of cryptotephra transport; the nature and timing of local site sedimentation; sampling considerations and subsequent taphonomic processes. Overall, while tephrostratigraphy has the

potential to improve significantly the chronology of such sites many limiting factors currently impacts the successful application.

1. Introduction

It has been observed that tephrostratigraphy and tephrochronology have the potential to be of major significance to the study of the environmental history of the Last Termination, c.18-8 ka BP (Davies et al., 2002; Turney et al., 2004, 2006). Tephra layers, once securely identified, provide the means to accurately link and synchronize diverse sedimentary records including terrestrial and marine palaeo-environmental and archaeological sites, with their archives of palaeoclimate and past human behaviour (Lowe 2011). Developments in the detection, isolation and characterisation of cryptotephra (Turney, 1998; Blockley et al., 2005) have allowed tephrostratigraphy to be applied to more situations than hitherto was the case (Davies et al., 2002) including the application to archaeological settings (Balascio et al., 2011). The new contexts open up interesting developments, but as this paper demonstrates, do not come without attendant complexities for the taphonomy of the depositional layers have an all-important influence. Recovery of trustworthy data is not always straightforward and is dependent on multiple, sometimes interrelated, factors.

The focus of this paper is the application of tephrostratigraphy to distal Late Palaeolithic sites in northern Europe which date from the Last Termination (i.e. the Oldest Dryas, Bølling, Older Dryas, Allerød, Younger Dryas and Preboreal Chronozones). The research took place in the context of the RESET research initiative, a 5-year Consortium funded by the UK's Natural Environment Research Council (NERC). The aim of RESET was to bring together archaeologists, volcanologists, tephrochronologists and stratigraphers to investigate the chronology of major phases of human dispersal and development in Europe in the past 100,000 years, and to examine the degree to which these were influenced by abrupt environmental transitions (http://c14.arch.ox.ac.uk/reset/). A survey of Late Palaeolithic sites from north of the Alps, Sudeten, Tatra and Carpathian mountains reveals only one-fifth have identifiable cryptotephra. Tephra is detected in both organic and minerogenic sediments, however depositional context, temporal duration of sediment accumulation and site taphonomy appear to be important influencing factors.

2. Tephrostratigraphy in the context of the north European Late Palaeolithic

2.1 The Principles and Application of Tephrostratigraphy

Tephrostratigraphy is a method for correlating diverse sedimentary sequences, whether they are palaeoenvironmental, geological or archaeological in nature. It has the advantage over many other chronological tools in that the precision is commonly significantly better (Lowe, 2011). The use of tephra is grounded in the principle that layers are deposited in a stratigraphic sequence and the position is governed by the Law of Superposition (Feibel 1999). If a tephra layer can be identified and characterised, it can be correlated to another tephra layer in another locality and this links the two loci in time (Westgate and Gorton, 1981). Matching of tephra layers can be done by physical properties in the field or using single grain geochemical analyses in the laboratory (e.g. electron microprobe WDS-EPMA and LA-ICP-MS). In some instances the palaeoenvironmental or palaeoclimatic context of a tephra in conjunction with its geochemical-signature may be significant thus allowing correlation (the Borrobol and Penifiler, Vedde Ash and AF555 tephras are prime examples of this, see Matthews et al., 2011). Where an existing age for the tephra is known, be it from historical records, radiometric dating (e.g. ^{14}C or Ar-Ar; Sarna-Wojcicki, 2000), or an incremental archive (e.g. varves or ice core layers; Grönvold et al., 1995), the age may be transferred from one locality to another provided compositional properties, e.g. chemical characteristics, are the same. In such situations tephrostratigraphy becomes tephrochronology, a powerful tool for dating.

Many factors potentially limit the application of tephrostratigraphy (Lowe 2011). Those of most relevance in the context of this investigation are:

(i) The possibility of tephra being reworked leading to the dissemination or remobilisation of glass shards. This can significantly influence whether correlation is feasible as reworked (remobilised) tephra form diachronous, rather than isochronous, surfaces. The non-reworked part of a tephra deposit does provide an isochron of maximum age (the date of the tephra eruption and primary deposition) but any reworked components are always younger.

(ii) The vertical spread (dissemination) of shards in a vertical profile may conceal the exact point in the sediments where a primary tephra layer was deposited.

(iii) Patchy tephra distribution patterns in peat deposits have sometimes been attributed to post-depositional processes associated with fallout on snow cover, including re-deposition by wind and meltwater. Snow entrapment, wherein cold conditions with little or no summer melt cause a significant lag between the initial deposition of ash and its subsequent deposition into a lake, was identified by Davies et al. (2007) as another factor that could lead to an incorrect interpretation of the true position of the tephrostratigraphic isochron in cold environment lacustrine deposits.

(iv) Multiple profiles will sometimes document periods of erosion and reworking, revealing differential effects even when distances are small. Within-site variability is a factor, suggesting that local geographic and stratigraphic taphonomic processes may be complex, requiring careful study and interpretation. Boygle (1999) and Pyne-O'Donnell (2011) highlight the drawbacks of single profile crypto-tephrostratigraphic surveys.

(v) Repeated eruptions may sometimes result in chemically similar geochemical datasets. Indeed many Icelandic tephra produced by different eruptions tend to have very similar major element geochemical compositions (Larsen and Eiríksson, 2007). External dating control may be required to differentiate temporally-separate, but compositionally similar, tephra.

Tephra detection, albeit the crucial starting point in a tephrostratigraphical study, is not sufficient on its own; there are many ancillary requirements if good chronological data are to come from the presence of tephra on an archaeological site.

2.2 Linking Volcanic Ash Layers and Late Palaeolithic Archaeology

Association between Late Palaeolithic archaeology and tephra is most commonly observed in areas proximal to active Late Pleistocene volcanoes. In such settings volcanic and archaeological layers may be readily observed and characterised in the field. Association between archaeology and volcanic eruption need not be direct, for volcanic sediments can overlie abandoned sites. Lateglacial northern European examples of this include the open-air Magdalenian sites of Andernach-Martinsburg and Gonnersdorf in the middle Rhine, which were discovered beneath thick Laacher See tephra (LST) deposits (Baales et al., 2002); and the Grotte du Coléoptère in the Ardennes, a Magdalenian cave site in which the occupation horizon was covered by tephra of the same east Eifel-sourced eruption (Dewez 1975; Juvigné 1977).

More direct ‘Pompeii-like’ association between ash-fall and cessation of human occupation would be expected but are not easily demonstrated in the Lateglacial of north Europe. The situation at l'Abri Durif à Enval, a rockshelter in the commune de Vic-Le-Comte, Puy-de-Dôme excavated between 1969 and 1979 by Yves Boudelle, illustrates some of the complexities. On this site volcanic ash was identified in layers I, II and IV in direct contact with a Magdalénien supérieur occupation horizon (Boudelle 1979). The tephra originates from the French Massif Central and is dated to 12 010 ± 150 ^{14}C yr BP (GifTan-91102). On the basis of geochemistry Vernet and Raynal (1995) correlate it with the eruption of La Tephra des Roches. However direct contact is not enough to demonstrate a causal connection between ash-fall and human abandonment since subsequent reworking may bring remobilised tephra into contact with archaeological material. Layer Ia on l'Abri Durif à Enval « … contained a large amount of volcanic ash. These ashes are in contact with the flints and bones found in this level (0.02 m)». This would suggest direct association, whilst the ash in the underlying layers

(Niveau Ib, II and IVa) could represent remobilised tephra. Residuality of archaeological material needs to be considered. For these reasons, in the absence of compelling associations, direct linkage of ash-fall to human abandonment is hard to prove.

Visible ash horizons may sometimes be observed in contact with archaeological material in distal and mid distal settings. The early Upper Palaeolithic sites in Kostenki-Borshchevo (Sinitsyn 2001; Anikovitch 2005; Anikovitch et al., 2007) are examples which have been known for many years (Melekestsev et al., 1984). At Kostenki-Borshchevo aeolian reworking of the tephra together with cryoturbation is believed responsible for making a 1-2 cm ash-fall into 10-30 cm in thickness horizons (Pyle et al., 2006). Distance from source in this instance is 2250 km. Bettenroder Berg IX in the valley of the River Leine in central Germany is a Lateglacial example of a visible volcanic layer on a mid distal site located 280 km from source. Here layer 17a – an occupation horizon of the Federmesser-Gruppen technocomplex is overlain by layer 16, a substantial 20-40 cm thick primary deposit of LST, demonstrating thickness and distance from source are influenced by the dynamics of ash transport, fall and sedimentation (Riede, 2008; Riede et al., 2011). This example would appear to represent the rapid fallout of very fine ash occurring as 'mass deposition', the result of meteorological aggregation processes a few hundred kilometres downwind of the emitting source.

In distal localities removed from the eruptive vent, recognition of tephra by the naked eye is rarely possible. However, development of laboratory processing methods (Turney, 1998; Blockley et al., 2005) have allowed systematic screening for cryptotephra so that the ash 'footprints' of eruptions have been significantly extended into new geographical regions. Bearing these points in mind, attention now turns to cryptotephra, which are subject to additional constraints.

3. Cryptotephra associated with Late Palaeolithic sites

Between 2008 and 2012 thirty-four north European Late Palaeolithic sites were investigated for cryptotephra (**figures 1a and 1b**). On- and off-site loci were sampled. On-site locations had *in situ* Late Palaeolithic or early Mesolithic archaeology (**table 1, figure 2**), whilst off-site contexts were natural sediments which accumulated concurrent with nearby human activity (typically c.10-300 m distant). **Tables 2 and 3** summarize the results, recording the presence/ absence of cryptotephra. Supplementary Materials (**S2**) contains an individual site-by-site compendium, and (**S3**) details the methodology used. Because individual site studies appear elsewhere (Brock et al., 2011; Housley et al., 2012, 2013, 2014a, b, c; MacLeod et al., in prep.; Tipping et al., in prep.; Torksdorf et al., 2013; Weber et al., 2010) this paper focuses on only the broad patterns.

Seven sites yielded identifiable analysable tephra, a success rate of 21% (**table 4**). Thirty-two sampling localities were open-air sites, with only two caves / rockshelters. Neither of the latter recorded cryptotephra but two is too small a sample to properly assess the viability of such sediment traps. The low representation of caves and rockshelters reflects a sampling bias to the North European Plain, where sites such as these are rare.

In the first stage of processing, where bulk 5-10 cm depth samples were examined, a few sites yielded occasional isolated tephra shards. Such records may be accessed from the RESET database (Bronk Ramsey et al., this volume). Bulk samples with isolated shards proved impossible to process further or prepare for geochemical analysis and have been excluded from the 7 'successful' sites. Precisely what this 'background' level of tephra represents is difficult to define – very low input, residual material, disturbance and reworking may all be responsible.

With exceptions, most sites were associated with one of several lithics industries (techno-complexes: Magdalenian, classic Hamburgian, Havelte, Federmesser and Ahrensburgian. However, some sites had more than one industry (e.g. Dourges, Sowin 7). Approximate dating of the archaeological techno-complexes is presented in **table 1**. Palaeoenvironmental archives could be proximal to more than one Late Palaeolithic activity area (e.g. Węgliny) or featured both on- and off-site archaeology (e.g. Lille Slotseng). Non-diagnostic lithics assemblages were encountered, inhibiting typological classification (e.g. Strumienno). Selection of sites was sometimes deliberate –

to target key Palaeolithic sequences (e.g. Pincevent, Étiolles and Neuchâtel) – at other times opportunistic, governed by access considerations (e.g. Wesseling-Eichholz, Lengefeld). Archived sediment was used where advantageous, or where original deposits have been removed (e.g. Reichwalde) or have become inaccessible (e.g. Neuchâtel). The degree of sampling in part reflected availability of open sections, stored material or known taphonomic issues. Absence of reported tephra from a site does not mean future cryptotephra sampling should be avoided if better sequences come available. On some sites we only undertook limited sampling - for further details, see the site compendium (**S2**).

What follows is an assessment of the factors which potentially influence the presence and deposition of cryptotephra on north European Late Palaeolithic archaeological sites.

3.1 Influence of Sedimentary Context

Given the diverse sedimentary contexts from where archaeological material of this age is recovered, it was deemed important to examine this variable to determine if this was indeed a governing factor. To assess whether the nature of the sedimentary matrix was influencing the cryptotephra record a simple classification system for describing the depositional matrix was applied. Sediments of this age are varied and hence what is presented here inadequately describes the complexities, though a simple grouping of broadly similar deposits helps identify common patterns in the data. Four categorizations are recognised for sedimentary context of the tephra layers:

1. Predominantly minerogenic sediments (i.e. sands, silts, clays, with/without larger stone clasts);
2. Predominantly organic sediments (i.e. peat, detritus mud, marl, gyttja);
3. Contexts where the zone of tephra extends over a stratigraphic boundary, thus the same tephra is present in both a minerogenic and an organic sediment unit;

4. Mixed contexts, the result of either human activity or pedogenic processes. Soil micromorphology is often needed to establish this.

This classification informs **tables 2-4**. Although twice as many on-site contexts were sampled (respectively, n=23 and n=11) the data show off-site contexts preserved cryptotephra layers better. Of the off-site contexts 36% recorded one or more cryptotephra (n=4, t=11), only 13% of on-site contexts had tephra (n=3, t=23). Organic and minerogenic sediments are represented in both settings, although archaeological remains were commonly associated with aerobic minerogenic sediments and anaerobic organic deposits were better represented in off-site locations. The pattern is clear however, off-site organic contexts result in better cryptotephra preservation than on-site minerogenic sediments.

3.2 Influence of Geographical Position

We observe a clear weighting to better tephra representation on sites from northerly latitudes (**table 4c**). This conclusion is simplistic and misleading, however. Iceland is the major volcanic source for northern Europe and prevailing winds carry the ash eastwards, with greater quantities of ash falling in northerly latitudes. The study by Lawson et al. (2012) is particularly important in understanding the spatial patterning of tephra originating from Iceland. Based on 22 eruptions in the last 7 ka, the investigation observed that past ash plumes have shown a wide range of behaviour in that they can be dense and widespread (e.g. Hekla 4); spatially patchy but widespread (e.g. Hekla 3); restricted to one region but found at practically all sites within its bounds (e.g. Glen Garry); or restricted to one region and patchily distributed within it (e.g. Hekla 1510). Based on space-, air- and ground-based monitoring and research reported following the Eyjafjallajökull 2010 event, the patchiness of tephra distributions would seem to be consequent on varying prevailing atmospheric conditions. We believe this patchiness is particularly important to this study.

In relation to the late Pleistocene previous research has shown the ash foot print of the Vedde Ash extends south to the Alps (Blockley et al., 2007). This distribution is explicable however by different atmospheric conditions in Europe during the Younger Dryas Stadial (Isarin et al., 1998; Brauer et al., 2009). A more accurate conclusion would be that two contributing factors influence the presence of cryptotephra: proximity to a volcanic source is clearly important but so is location downwind of an emitting centre – hence Scandinavia, the British Isles and northern Europe have a record of Icelandic volcanic activity whereas the Balkans record eruptions originating in Italy. Regardless of other influences, tephra must first be present in a region for it to be preserved. For this reason some parts of Europe are more likely to be impacted by tephra than are others (Davies et al., 2010; Lawson et al., 2012).

3.3 Influence of Site Taphonomy

We hypothesize that cryptotephra is less likely to be recognised on archaeological sites if ash-fall occurs in periods of human occupation. This is because disturbance by humans and non-continuous sedimentation will inhibit discrete accumulation and preservation of discrete cryptotephra layers. Our open-air study sites have shallow stratigraphies with Lateglacial deposits commonly located near modern ground surface; biological activity, land-use practices and pedological processes were visible influences. Albeit weakly, the data in **table 2** appear to support this contention for two of the three sites with cryptotephra in on-site contexts (Ahrenshöft, Mirkowice) have cryptotephra over- or underlying the archaeological layer; Lille Slotseng, in contrast, has archaeology and cryptotephra in the same layer. However a 2:1 ratio does not make a compelling case and we conclude this hypothesis needs more investigation.

This point requires further qualification for although in Slotseng archaeological material is present in the same layer as tephra, no causal relationship can be demonstrated. Tephra is observed over 60 cm of vertical sedimentation in Slotseng, coinciding with the archaeological layer but also being present in the sediments above. The geochemistry is complex, suggesting at least three different rhyolite layers from Iceland, one of which has not been recognised previously (MacLeod et al., in prep.). Nothing in the archaeological supports the contention that Palaeolithic humans took particular account of the tephra to change their behaviour. The other study sites with in situ archaeology and cryptotephra, i.e. Ahrenshöft LA 58D (Weber et al., 2010; Brock et al., 2011; Housley et al., 2012) and Mirkowice 33 (Housley et al., 2014a) have their own accounts and factors. The linking theme to all these sites is the need for careful evaluation of site processes.

3.4 Sampling Bias and Local Sediment Hiatuses

Many of our more southern sites date from the late Magdalenian period (approximately the Bølling Chronozone). Geographically those in Germany and Poland could be expected to be situated within the ash fall zone of the Laacher See Tephra, however we detected little presence of this tephra. It is possible sample selection had a part to play, for example if sampling did not extend sufficiently high in the stratigraphic sections to take in the end of the Allerød. However, this is unlikely to be true for all sites in that, where feasible we extended sampling into the early Holocene. We can only conclude that either this reflects an inherent patchiness to tephra distributions, or some of the sequences we sampled have unrecognised periods of hiatus. This temporal 'patchiness' is perhaps more common with the onsite aerobic sediments than the offsite anaerobic contexts.

4. Conclusions

This is no more than a beginning. The parallel study by Swindles et al. (2013) is of particular relevance in this context, albeit the focus of their investigation is re-deposited cryptotephra in Holocene peats linked to anthropogenic activity. Whereas Balascio et al. (2011) report a single site investigation of a distal cryptotephra found in a Viking boathouse in Iron Age Norway, our study focuses on fisher-gatherer-hunter sites from the Last Termination. General lessons for future cryptotephra research in the context of such sites are:

- Cryptotephra do survive directly on Late Palaeolithic open-air sites, whether the sediments are minerogenic (e.g. Mirkowice) or organic (Lille Slotseng). But the frequency of survival is relatively low.

- There appears to be a general patchiness to tephra distributions but it is not easy to resolve if this is due to atmospheric factors influencing the availability of tephra in an area, the input of tephra into a sedimentary environment, or hiatus periods within sediment accumulation on particular sites.
- Geographical position in relation to emitting volcanic centres is significant.
- Detection may require the analysis of multiple profiles, from both on-site and off-site contexts.
- Site taphonomy is important, with local depositional conditions and subsequent processes appearing to play a crucial role in the preservation of recognisable tephra marker horizons.
- Continuous low energy sedimentation favours preservation. Where concentrations of cultural finds are high, sedimentary deposition is intermittent, and bioturbation is attested, the probability of successful tephrostratigraphic study diminishes.
- Although cryptotephra research may best be concentrated in lower energy sediments, to permit integration with archaeological interpretations one ideally needs good stratigraphic correlations between off-site contexts and the main human activity areas.
- Making connections between human activity on dry land and anaerobic palaeoclimate archives is challenging. However, future methodological developments, e.g. applying lipid biomarkers to lacustrine environments (Holtvoeth et al., 2010) to detect the presence of neighbouring human activity, may facilitate correlation of profiles thereby allowing for the greater application of tephrostratigraphy within archaeology.

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Captions

Figure 1a: Map of sampling localities, 'circles' represent sites with analysable cryptotephra, 'plus' and 'square' symbols are respectively open-air and cave/rock shelter sites with no cryptotephra.

Figure 1b: Map of sampling localities showing the archaeological stone tool techno-complexes. Approximate dating for these techno-complexes is shown in **table 1**.

Figure 2: Chronostratigraphical sequence of the Last Termination in relation to the NGRIP and GRIP ice cores ($\delta^{18}O$ per mil), Icelandic and Eifel volcanic eruption record from the RESET database (Bronk Ramsey et al., this volume); INTIMATE events and episodes from Lowe et al. (2008); ^{14}C dated sites (human remain, cut-marked bone and bone/antler tool samples) by region and open-air site / rock shelter or cave (updated S2AGES database of calibrated radiocarbon estimates from western Europe in the period 25,000–10,000 years ago: Gamble et al., 2005). Saksunarvatn, Askja 10-ka, Abernethy AF555, Vedde Ash, Laacher See Tephra, Penifiler and Borrobol Tephras have been highlighted in red.

Table 1: Chronostratigraphy of the Last Termination and the archaeological stone tool techno-complexes for the regions sampled (after Reide et al. 2010; Terberger 2006; Weber and Grimm, 2009).

Table 2: Seven northern European sites analysed between 2008 and 2012, with Late Palaeolithic archaeology and confirmed cryptotephra layer(s).

Key to table 2: 'on-site' – sediments where archaeology is present in the sampled profile; 'off-site' - nearby palaeoclimate archives sampled; "(A)" – inferred position of archaeology where tephra is detected in an off-site setting; (A) – direct in situ position of archaeology where tephra is detected on-site; see colour key for sediment categorization.

Key to references: (1) Brock et al., 2011; (2) Housley et al., 2012; (3) Housley et al., 2013; (4) Housley et al., 2014b; (5) Housley et al., 2014c; (6) Housley et al., 2014a ; (7) MacLeod et al. (in prep.); (8) Tipping et al. (in prep.); (9) Torksdorf et al., 2013; (10) Weber et al., 2010.

Table 3: Twenty-seven north European Late Palaeolithic sites sampled 2008-12 with no significant tephra. Key: HRT/RT: Hauterive/Rouge-Terre; ‘On-site’ - sediments with archaeology; ‘Off-site’ – off-site deposits believed contemporary with Late Palaeolithic archaeology; ‘brown’ - minerogenic aerobic sediments; ‘green’ – peat / detritus mud / gyttja anaerobic sediments.

Table 4: Summary of cryptotephra presence/absence by type of site, associated sedimentation and by latitude of location.

Table 1

<table>
<tr><th>Greenland stadial / interstadial</th><th>Chronozone</th><th colspan="3">Techno-complex</th></tr>
<tr><td>Holocene</td><td>Pre-boreal</td><td colspan="3">Early Mesolithic</td></tr>
<tr><td>GS-1</td><td>Younger Dryas</td><td colspan="2">Ahrensburgian</td><td rowspan="4">Late Palaeolithic</td></tr>
<tr><td>GI-1a
GI-1b
GI-1c1
GI-1c2
GI-1c3</td><td>Allerød</td><td>Federmesser Groups (FMG)</td><td>Bromme</td></tr>
<tr><td>GI-1d</td><td>Older Dryas</td><td rowspan="2">Late Magdalenian</td><td>Havelte</td></tr>
<tr><td>GI-1e</td><td>Bølling (Meiendorf)</td><td>Hamburgian</td></tr>
</table>

Table 2

Site	Howburn Scotland UK	Ahrenshöft LA58D N Germany	Grabow N Germany	Oldendorf / Schünsmoor N Germany	Lille Sloseng Denmark	Węgliny SW Poland	Mirkowice 33 NW Poland
Location	55 40' 22" N 3 29' 1" W	54 33' 57" N 9 6' 29" E	53 00' 41" N 11 7' 00" E	53 15' 28" N 9 14' 39" E	55 16' 14" N 9 20' 5" E	51 49' 57" N 14 43' 30" E	52 46' 27" N 17 24' 18" E
Context	Offsite	Onsite	Offsite	Offsite	Onsite	Offsite	Onsite
Late Holocene			**AD1875 / Glen Garry Askja Iceland**				**Glen Garry Askja Iceland**
Early Holocene		**Suðuroy / AF555 tephra / Vedde Ash Katla Iceland**		**Suðuroy / AF555 tephra / Vedde Ash Katla Iceland**		**Hasseldalen Snæfellsness Iceland**	
Younger Dryas (GS-1)	**Vedde Ash Katla Iceland**				**Vedde Ash Katla Iceland**		
Late Allerød (GI-1a)						**LST Laacher See East Eifel**	
Early Allerød (GI-1c)						**T642/655 East Eifel**	
Bølling (GI-1e)					**Borrobol / Torfajökull Iceland**	**Borrobol / Katla / Snæfellsness Iceland**	
Late Pleni-glacial (GS-2)							
Reference	8	1, 2, 10	5, 9	4	7	3	6

aeolian

fluvial / limnic minerogenic sediments

organic

organic & minerogenic sediments

'mixed' sediments

Table 3

Country	France	Belgium	Luxembourg	Switzerland	Germany	Denmark	Poland
Site	Dourges	Arendonk De Liereman	Alzette Valley	Neuchâtel (HRT/RT)	Tolk	Hasselø	Łęgoń 5
Location	50 26' 57" N	51 19' 45" N	49 43' 10" N	47 0' 40" N	54 34' 30" N	54 43' 54" N	51 46' 9" N
	2 58' 27" E	5 2' 25" E	6 7' 2" E	6 58' 42" E	9 37' 22" E	11 52' 48" E	16 23' 19" E
Context	Onsite	Onsite	Offsite	Offsite	Offsite	Offsite	Offsite
Site	Étiolles	Lommel Maatheide			Wesseling-Eichholz	Lundby Mose	Olbrachcice 8
Location	48 38' 3" N	51 13' 53" N			50 48' 10" N	55 6' 11" N	51 46' 29" N
	2 27' 52" E	5 15' 39" E			6 58' 54" E	11 51' 52" E	16 22' 24" E
Context	Onsite	Onsite			Onsite	Onsite	Onsite
Site	Pincevent	Opgrimbie			Breitenbach		Siedlnica 17 & 17a
Location	48 22' 7" N	50 57' 13" N			51 33" N		51 45' 47" N
	2 53' 34" E	5 38' 52" E			12 5' 3" E		16 21' 58" E
Context	Onsite	Offsite			Onsite		Onsite
Site					Lengefeld		Strumienno
Location					51 6' 49" N		52 3' 25" N
					11 42' 18" E		15 2' 51" E
Context					Onsite		Onsite
Site					Reichwalde		Dzierzyslaw 35
Location					51 24' 11" N		50 2' 58" N
					14 42' 14" E		17 59' 18" E
Context					Offsite		Onsite
Site					Hohle-Fels		Sowin 7
Location					48 22' 48" N		50 33' 18" N
					9 45' 16" E		17 37' 48" E
Context					Onsite		Onsite
Site					Hohlenstein-		Cmielow 95
Location					48 32' 58" N		50 52' 58" N
					10 10' 21" E		21 32' 5" E
Context					Onsite		Onsite
Site							Podgrodzie 16
Location							50 54' 00" N
							21 33' 42" E
Context							Onsite
Site							Hłomcza
Location							49 37' 46" N
							22 16' 43" E
Context							Onsite

Table 4

Table 3a

	tephra		no tephra		total
Open sites	7	22%	25	78%	32
caves / rockshelters	0	0%	2	100%	2
Total no sites	7	21%	27	79%	34

Table 3c

	Tephra Presence vs Site Latitude								
Latitude	55°N	54°N	53°N	52°N	51°N	50°N	49°N	48°N	47°N
Sites with tephra	2	1	2	1	1	0	0	0	0
Sites without tephra	1	2	0	1	9	7	2	4	1

Table 3b

	tephra		no tephra		total
onsite organic	3	**13%**	2	87%	23
onsite minerogenic			18		
offsite organic	4	**36%**	6	64%	11
offsite minerogenic			1		
Total no sites	7		27		34

Figures 1a & 1b
Click here to download high resolution image

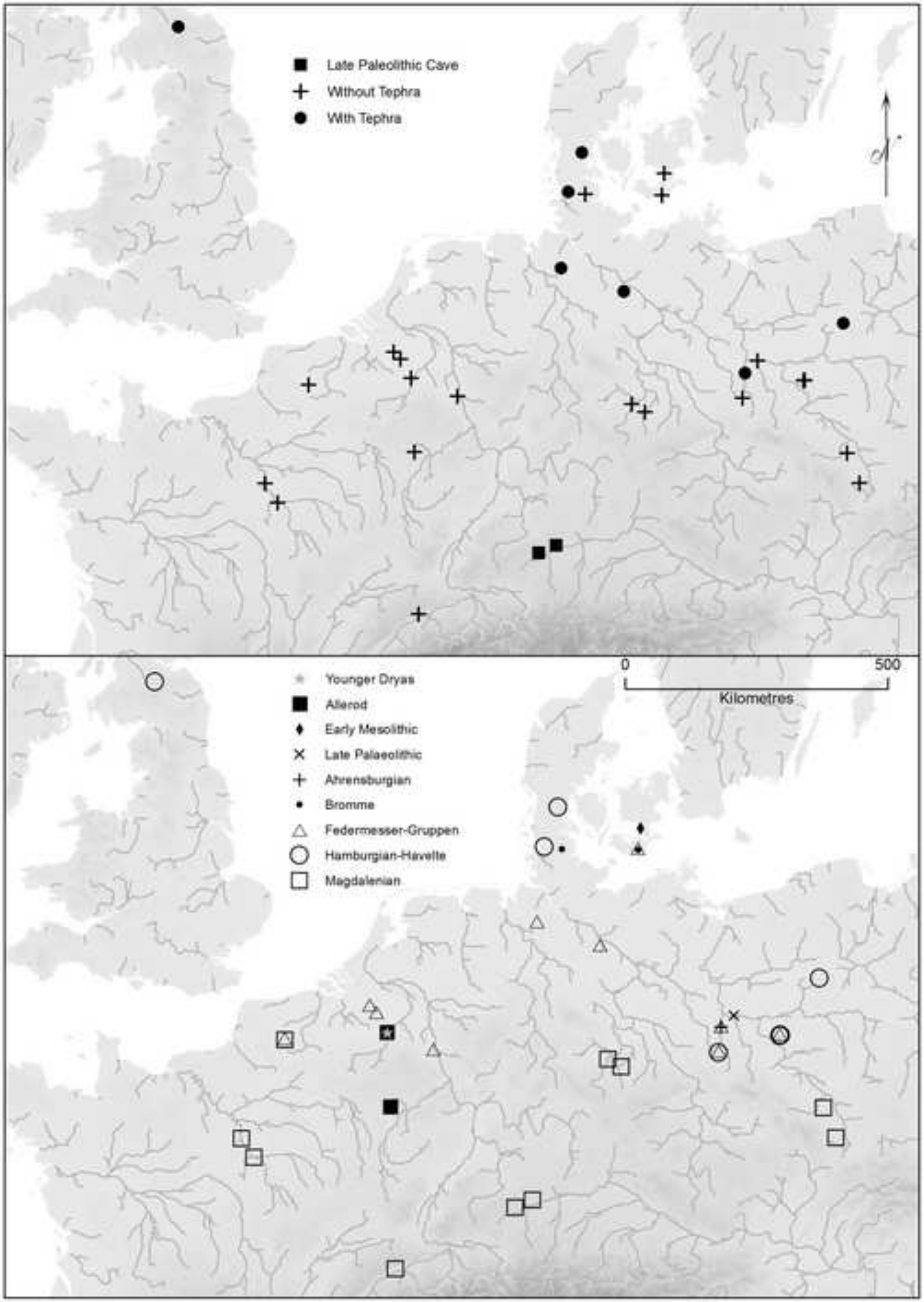
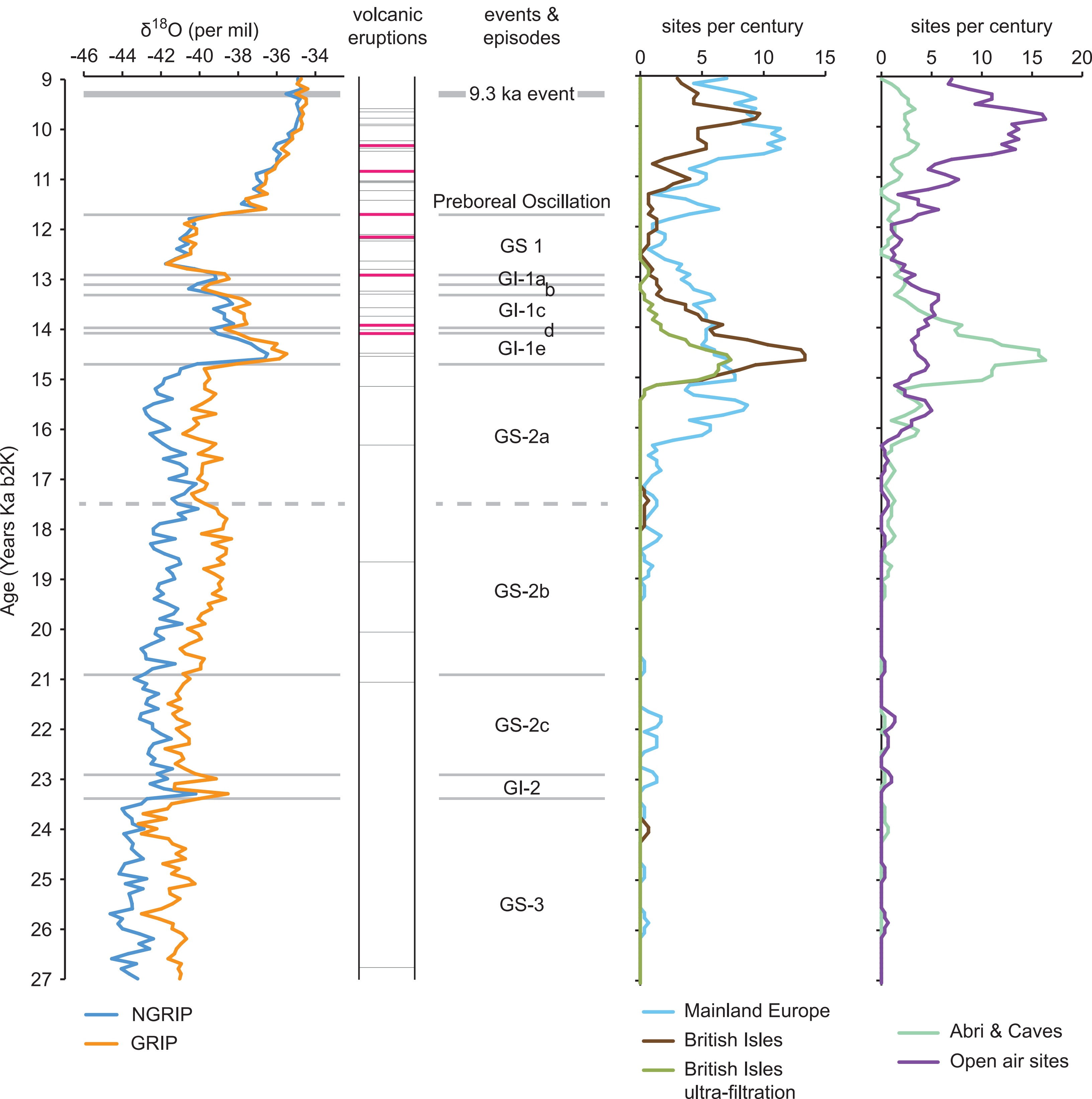


Figure 2


δ18O (per mil)
-46 -44 -42 -40 -38 -36 -34
volcanic eruptions
events & episodes
sites per century
0 5 10 15
sites per century
0 5 10 15 20
Age (Years Ka b2K)
9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27
9.3 ka event
Preboreal Oscillation
GS 1
GI-1a
b
GI-1c
d
GI-1e
GS-2a
GS-2b
GS-2c
GI-2
GS-3
NGRIP
GRIP
Mainland Europe
British Isles
British Isles ultra-filtration
Abri & Caves
Open air sites

Supplementary Data S2

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Supplementary Data S3

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KML File (for GoogleMaps)

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